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THE UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

A STUDY OF THE EFFECT OF VISCOSITY RATIO ON THE DISPLACEMENT OF MISCIBLE FLUIDS IN POROUS MEDIA

A THESIS
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
degree of
MASTER OF PETROLEUM ENGINEERING

BY
F.loyd W.arren GOOCH, JR.
Norman, Oklahoma
1949

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A STUDY OF THE EFFECT OF VISCOSITY RATIO ON THE DISPLACEMENT OF MISCIBLE FLUIDS IN POROUS MEDIA

A THESIS

APPROVED FOR THE DEPARTMENT OF PETROLEUM ENGINEERING

BY______________________________

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A STUDY OF THE EFFECT OF VISCOSITY RATIO ON THE DISPLACEMENT OF MISCIBLE FLUIDS IN POROUS MEDIA

CHAPTER I

INTRODUCTION

Within recent years the increasing demand for petroleum products and the realization that the supply of new sources of petroleum is not inexhaustible have focused attention on the fact that in most of our oil production in the past, only about one third of the oil originally present in the reservoir is recovered when the economic limit is reached. This figure applies only when the field is produced by conventional methods where the main source of energy is the gas dissolved in the oil.

With this in mind many investigators have sought to find ways both to remove the residual oil and to improve methods of production so that a much greater per cent of the oil is removed initially.

Two methods are in common use today to remove the residual oil after primary depletion. Both of these methods involve displacement of the residual oil by another fluid. In one method gas and the other method water is used as the

displacing fluid. Although both of these methods have been applied in the field for a number of years and much laboratory work has been done on the displacement of oil by another fluid in a porous media, there still remains a large number of problems to be solved before the mechanics of displacement of fluids in a porous media is completely worked out. Many investigators are now working on these problems with the idea of gaining more complete recovery of petroleum from the reservoir.

CHAPTER II

REVIEW OF PREVIOUS INVESTIGATIONS

The initial study of flow of liquids through sands dates back to 1856 when H. d'Arcy (1)* performed his experiments on the flow of water through sand. In 1898 King (2) measured the rate of flow of water and air through consolidated and unconsolidated sands and published the results. It was not until 1920, when the increasing demand for oil caused the U.S. Bureau of Mines to make a series of experiments on flow characteristics of oil and water, that additional work was done on flow of fluids in a porous media. By 1930 the importance of flow measurements to production of gas and oil was realized and in the ensuing years the investigations of Cloud (3), Nutting (4), Wyckoff, Botset and Muskat (5), and many others added materially to our knowledge of fluid flow in porous media.

In the last ten to fifteen years most of the work has been directed toward the development and improvement of methods of predicting petroleum reservoir performance. As a result there have been numerous investigations made of the behavior of immiscible fluids in porous media. Leverett (6),

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*Numbers in parenthesis refer to references in the bibliography.

Leverett and Lewis (7), and others have contributed much to the development of the theory and mechanics of the displacement of oil by water. Information concerning the displacement of oil by gas was reported by several investigators such as Reid and Huntington (8), Botset (9), and Buckley and Leverett (10). The latter worked out a satisfactory picture of the mechanics of the displacement of oil by both water and gas.

However, while the above work was being carried out with immiscible fluids, little work was done on the mechanics of displacement of two miscible fluids. Berts (11) and Dunker (12) investigated the effects of specific gravity, velocity and pressure on the amount of mixing taking place during the displacement of one gas by another in unconsolidated sand. They concluded that the amount of mixing was inversely proportional to the rate of flow and that it became less as the pressure was increased up to a certain point for any given linear velocity. Above this point an increase in pressure caused an increase in the amount of mixing. Their experiments also indicated that less mixing took place when the heavier gas was made the displacing fluid.

Russel, Morgan and Muskat (13) in studying the mobility of interstitial waters arrived at some conclusions concerning the displacement of water by water in a consolidated sand. Their results in all cases showed that after injecting into the core a volume of displacing water equal to one pore

CHAPTER III

STATEMENT OF PROBLEM

This problem was undertaken to study the displacement of one fluid by another miscible fluid in a porous media. As in all problems of fluid displacement there are several variable factors involved. These factors are:

(1) Physical characteristics of the porous media

(2) Chemical characteristics of the porous media

(3) Viscosity of the fluids

(4) Specific gravity of fluids

(5) Differential pressure or rate of displacement

Since the experiment was undertaken primarily to obtain information of a fundamental nature it was thought best to vary only one factor and to maintain all other factors constant. When it became evident during the course of this investigation that the force of gravity was affecting the results due to the displacement taking place with the core in a horizontal position, a series of similar drives were made with the core in a vertical position to determine the magnitude of the gravity affect.

This investigation was prompted by the fact that

CHAPTER IV

MATERIALS

The synthetic core that was used in this work consisted essentially of pure quartz grains partially consolidated by silica. This core was contained in a cylindrical Lucite tube, 100 centimeters in length and 6.35 centimeters inside diameter.

To make this core Oil Creek sand, obtained from an outcrop near Sulphur, Oklahoma, was sieved and a fraction between 80 and 140 mesh retained. This sand was thoroughly washed with hot water then cleaned by agitation in hot hydrochloric acid. Following this it was again washed with water then agitated in a hot sodium hydroxide solution with a final wash with water until the solution was shown by litmus paper to be neutral. The sand was then placed in an oven to be dried. After drying was complete the sand was resieved with the 80 to 140 mesh fraction again retained.

Next the Lucite tube was fitted with square end plate cut from one inch sheet Lucite. A circular groove 3/16 inch deep, 6.35 centimeters inside diameter, and 7.75 centimeters outside diameter was machined in the face of each block and

a hole drilled and tapped for 3/8 inch threads in the center. Brass fittings and valves were threaded into these holes and a 130 mesh screen placed over the hole. The four corner of the two end plates were drilled to accommodate tie rods. Next a neoprene rubber gasket was put into the groove of one end plate and two tie rods were placed in opposite corners. This plate was fitted to one end of the Lucite tube, the two tie rods being secured at the other end in a wooden blank placed on the Lucite tube. Prior to putting on this blank a 6 inch extension of the same diameter tube was placed on the end of the long tube. The blank left this end of the tube partially open. The tube was then placed on a vibrating table in a vertical position with the end plate down and a length of rubber hose run from the brass fitting to a large beaker.

With the valve at the lower end closed Syton,* a colloidal suspension of silica in water, was poured into the top of the tube until there was approximately 3 inches of Syton in the tube. The cleaned sand was placed in a funnel which was clamped above the vertical tube. This allowed the sand to be fed slowly into the tube. Additional Syton was added to maintain its level approximately 3 inches over the sand as it was deposited into the bottom of the tube. This method was used to get uniform permeability and porosity in the core.

When the sand had been deposited even with the top of the long tube, the vibrating table was stopped, the tie rods

---

*Obtainable from the Monsanto Chemical Co., Boston, Mass.

loosened and the extension tube removed. The other end plate was put on and all four tie rods run through both end plates and pulled tight, thus sealing both ends of the tube. With the core still in the vertical position the valve on the lower end was opened and the liquid drained out. Then dry air was forced into the top and passed down through the sand and out the lower end of the tube thus displacing any remaining water and drying out the sand. After twenty-four hours of drying with air, the bottom valve was closed, a vacuum pump attached to the top of the tube and a vacuum placed on the tube for twenty-four hours. At the end of this time approximately 1000 cubic centimeters of alcohol ("Synasol") was forced into the core through the lower end. The core was again dried by passing dry air through it for a period of forty-eight hours and then maintaining a vacuum on it for twenty-four hours.

The above procedure resulted in a partially consolidated core of essentially pure silica. At this time a series of permeability tests were run with air on the core. These indicated an average overall permeability of 3.4 darcies. However, upon installing pressure taps every 33.3 centimeters along the core it was found that one end of the core had a low permeability compared to the other two sections. A piece 6.3 centimeters long was removed from this end of the core and air permeabilities again run. The overall permeability was found to be 3.28 darcies and none of the sections deviated more than 5 per cent from this value. Since this gave a

fairly uniform core it was deemed satisfactory for the experiments to be run on it.

The porosity of the core was determined next. The first method was to measure pressure at two different values and record the volume removed in going from the higher to the lower pressure. By using the perfect gas law the porosity was calculated to be .337. The other method was by the use of wet and dry weights. The fractional porosity in this case was calculated to be .307. This latter value was used in all calculations since it was felt that the method used in calculating this value was far more accurate.

The sugar solutions used in this work were made with distilled water and commercial cane sugar (sucrose). The index of refraction of the distilled water was checked before the addition of the sucrose, then after addition of sucrose the index of refraction was again taken and from this information the per cent of sucrose in the solution was calculated and thus the viscosity known.

CHAPTER V

EXPERIMENTAL APPARATUS

With the core partially consolidated and its permeability and porosity judged sufficiently homogeneous for this experiment, additional holes were drilled and tapped in the tops of the end plates and brass fittings were installed. With the core in the horizontal position, a copper spigot was installed at the outlet end, and a brass tee installed at the inlet end. With brass valves installed on both sides of the tee a means was provided for purging the fluid system before it entered the core. Manometer leads were connected to the fittings on both end plates.

Next a 2½ liter pyrex bottle with a bottom outlet was set up with a rubber stopper that had a hole in the center through which a copper tube extended into the bottle to a point near the bottom of the bottle. The tube and stopper were held in place by a metal fitting fastened to the bottle by fine copper wire. A brass tee was connected to the tubing before it entered the bottle and from one side of this tee copper tubing was run to a source of air. Air originally under 100 psi pressure was first reduced by a pressure

regulator to 60 psi. It was further reduced and regulated by a [illegible] Pressure Regulator which allowed a fine accurate control of the pressure over a range of 0 psi to 20 psi.

From the other side of the tee a lead was run to a mercury manometer. This measured the pressure existing at the end of the copper tubing in the bottle. Therefore, differences in fluid level in the bottle at various times during the runs would not affect the pressures placed on the system and a constant pressure could be maintained.

Since the level of the outlet of the copper tube in the bottle was adjusted to the same level as that of the inlet to the core, with a fluid connection to this inlet, the pressure at the inlet was the same as that measured at the end of the tube in the bottle.

Figure II shows the flow system used in this experiment. The components of this system are:

(A) High pressure regulator and reducer
(B) Low pressure regulator and reducer
(C) Mercury manometers
(D) Pyrex bottle fluid reservoir
(E) Valve for purging fluid system
(F) Synthetic core
(G) Valve and spigot at outlet
(H) Manometer connections
(I) Graduate
(J) Screen type filter

For the runs made in the vertical position essentially the same set up was maintained and a correction was made for the difference in height of the inlet to the core and the point where the pressure was measured in the bottle.

From Figure II it can be seen that the flow system consists only of applying air pressure to the bottle (b) which causes the fluid in the bottle to flow through the filter to the inlet of the core, then passing through the core to the outlet where it is caught and measured in the 500 cubic centimeter graduate (I).

The apparatus used to measure the per cent of sugar in the efflux stream was a Spencer Abbe-type Refractometer. This refractometer is accurate to the third decimal place. From the knowledge of the amount of sugar in the efflux stream the per cent of original fluid could be calculated.

CHAPTER VI

EXPERIMENTAL PROCEDURE

After completing the partial consolidation and drying of the core, a series of permeability tests were run with air. On the completion of the permeability tests porosity was obtained by two different methods. When the permeability and porosity were deemed satisfactory the core was saturated with water and connected to a fluid system that was under a controlled pressure. Thus the water in the core could be displaced by another fluid which in turn could be displaced by another fluid. During these displacements, rate and composition of the efflux stream were measured.

Permeability Determinations

Upon running initial permeability test it was found that one end section of the core had a very low permeability compared to the other two sections. Upon removing the end plate it could be seen that a small hard plug had been formed in the center of the core. This plug appeared to extend into the core for only a few centimeters. Using a diamond saw approximately 6 centimeters was cut from the end of the core which was then squared by the use of fine emery cloth. This

resulted in a core 33.7 centimeters in length. When permeabilities were run on this core it was found to have an overall permeability of 3.98 darcies while the three sections had permeabilities of 3.81, 4.01, and 3.82 darcies. All of these permeabilities were determined in the usual manner using air. After the values were determined they were plotted against the reciprocal of the mean pressure at which they were obtained and extrapolated to an infinite pressure to correct for the Klinkenberg effect.

Porosity Determinations

Two methods were used to determine the porosity of the core. The first method was to build up a pressure in the core, record this pressure, then lower the pressure by metering out a known volume of air and again record the pressure. Applying the perfect gas law the volume of space the gas occupied in the core could be calculated. The total volume of the tube and fittings can be determined from their dimensions, thus the porosity determined. The average value found by this method was .337.

The second method used the difference in dry and wet weights of the core and was described in a previous section. The porosity by this method was found to be .307. This method was thought to be more accurate than the one using air, so it was used in all calculations.

Index of Refraction Measurements

The solutions used in this experiment were transparent, thus using the proper instrument the index of refraction could easily be measured. Since the per cent of sucrose in an aqueous solution is directly related to its index of refraction a measurement of this value could be converted easily to per cent of sucrose present.

In this work the index of refraction of both the original fluid in the core and of the displacing fluid were measured before a run was started. At regular intervals during the run index of refraction of the efflux was measured and with these values the per cent of the original fluid in the efflux could be calculated.

Experimental Runs

After the permeability and porosity determinations had been made on the core it was left saturated with distilled water which was displaced by an aqueous sucrose solution of known index of refraction. The pressure bottle was filled with distilled water, then connected to the air system and to the core by means of plastic tubing. (See Figure II.)

Next a pressure was applied to the system through the regulators which maintained this pressure constant. A valve at the outflow end of the core was opened allowing the original fluid in the core to be displaced by the sucrose solution. The volume of the displaced fluid and the rate of flow

of the effluent stream was measured and recorded at the same time the index of refraction of the efflux was obtained.

By referring to the tables in the Handbook of Chemistry and Physics (14), the per cent of sucrose by weight in the efflux was obtained. The temperature was measured and a correction applied to the above percentage. From another table in the Handbook the amount of sucrose (grams per liter) was obtained. Since the same values were obtained for the original sucrose solution the amount of the original fluid present in the efflux could be calculated. These measurements and calculations were made at regular intervals during the displacement process.

EXPERIMENTAL DATA

TABLE I

RUN NUMBER I

Temperature, 27° C

P = 200 mm. Hg.

Original Fluid (Distilled water)

nD = 1.3328

Viscosity = .8640 cp

Displacing Fluid (Sugar Solution)

n = 1.3710

Viscosity = 1.96 cp

% sugar = 24.72%

cu. cms. Produced	n = efflux	Fract. Pore Volume	% Sugar in eff.	Wt. of sugar in eff.	% of Displacing fluid in efflux	% Original fluid in eff.
830	1.3328					
900	1.3351	.962	1.4	14	5.17	94.8
905	1.3551	1.02	13.02	139	51.2	48.8
950	1.3659	1.05	21.00	235	86.2	13.8
975	1.3686	1.075	23.20	255	94	6.0
1000	1.3696	1.105	23.92	262	96.7	3.3
1050	1.3705	1.160	24.30	267	98.5	1.5
1150	1.3708	1.27	24.40	268	99.0	1.0
1200	1.3710	1.435	24.72	271	100	0

nD = Index of refraction.

TABLE II

RUN NUMBER 2

Temperature = 25° C   P = 820 mm. Hg.

Original Fluid (Sugar Solution)   Displacing Fluid (Distilled Water)

n = 1.3710   n = 1.3325

Viscosity = 2.00 cp.   Viscosity = .8937 cp.

% Sugar = 24.72%

cu. cms. Produced	n = efflux	Fract. Pore Volume	% Sugar in eff.	Wt. of sugar in eff.	% Original Fluid in eff.
500	1.3710	.552	24.72	270	1.00
600	1.3708	.662	24.45	268	.992
650	1.3690	.718	23.40	256	.950
700	1.3640	.773	20.49	220.5	.816
800	1.3548	.883	14.67	164	.61
850	1.3521	.938	13.08	137	.507
950	1.3470	1.048	10.02	104	.388
1000	1.3462	1.103	8.27	88.6	.317
1100	1.3418	1.213	5.52	54.5	.239
1200	1.3408	1.323	5.48	58	.207
1400	1.3361	1.545	2.40	25	.093
1600	1.3338	1.770	.65	6.8	.024
1700	1.3327	1.878	0	0	0
1800	1.3325				

TABLE III

RUN NUMBER 3

Temperature = 25° C   P = 250 mm. Hg.

Original Fluid (Sugar Solution)   Displacing Fluid (Distilled water)

n = 1.4088   n = 1.3325

Viscosity = 6.1 cp   Viscosity = .8937 cp

% Sugar = 45.05%

Cu. cms. Produced	n = efflux	Fract. Pore Volume	% Sugar in eff.	Wt. of Sugar in eff.	% Original Fluid in eff.
0	1.4088				
200	1.4088	.221	45.05	241	1.00
400	1.4059	.464	43.21	333	.934
500	1.3822	.552	33.30	452	.734
550	1.3777		28.30	302	.614
600	1.3664	.662	21.04	226	.456
650	1.3504		16.00	151	.354
700	1.34	.773	11.12	115	.244
750	1.3472		9.07	102	.198
800	1.3151	.883	12.32	130	.240
850	1.3463	.939	9.42	98	.181
1000	1.3472	1.105	9.07	102	.198
1065	1.3495	1.197	10.72	111	.238
1350	1.3472	1.490	9.07	102	.198
1725	1.3429	1.905	7.02	72	.155
1875	1.3412				
2000	1.3387	2.210	4.2	45	.0934
2600	1.3353	2.870	1.9	19	.036
3300	1.3349	3.640			
3750	1.3335	4.140			

TABLE IV

RUN NUMBER 4

Temperature = 25° C
Original Fluid (Sugar Solution)
n = 1.3910
Viscosity = 3.8 cp
% Sugar = 35.01%

P = 200 mm. Hg.
Displacing Fluid (Distilled Water)
n = 1.3325
Viscosity = .8937 cp

cu. cms. Produced	n = efflux	Rate cc/min.	Fract. Pore Volume	% Sugar in eff.	Wt. of sugar in eff.	% Original fluid in efflux
0	1.3910	4.8				
100	1.3910	4.6	.11			
200	1.3910	5.7	.221			
300	1.3910	6.02	.331			
400	1.3910	6.3	.442			
500	1.3910	6.6	.552	35.01	413	1.00
600	1.3785	7.3	.662	30.81	374	.783
650	1.3755	8	.717	27.21	305	.734
800	1.3635	8.6	.883	20.09	217	.525
900	1.3524	9.5	.993	13.22	138	.334
960	1.3490		1.060	10.37	113.5	.274
1000	1.3469	9.7	1.105	9.62	98	.259
1050	1.3457		1.160	8.97	91.5	.221
1120	1.3441	10	1.236	7.81	80	.193
1200	1.338	10.3	1.325	3.7	37	.0896
1300	1.338	10.3	1.435	3.7	37	.0896
1500	1.3371	10.5	1.655	3.1	31	.075
1600	1.3380	10.3	1.770	3.7	37	.0896
1700	1.3360	10.6	1.875	2.4	24	.0581
1800	1.3358	11.1	1.990	2.3	23	.0557
2050	1.3355	12.5	2.26	2.00	20	.0485
2300	1.3332	12.5	2.54	.45	45	.011

TABLE 7

RUN NUMBER 3

Temperature = 26° C
Original Fluid (Sugar Solution)
n = 1.3721
Viscosity = 2.06 cp
% Sugar = 24.70%

P = 760 mm. Hg.
Displacing Fluid (Distilled Water)
n = 1.3324
Viscosity = .8737 cp

cu. cms. Produced	n = efflux	Rate cc/min.	Fract. Pore Volume	% Sugar in eff.	Wt. of sugar in eff.	% original fluid in efflux
100	1.3715	37				
300	1.3711	42				
550	1.3710	62	.595	24.71	272.5	100
600	1.3700		.640	24.15	265	97.3
650	1.3680		.695	22.95	250.5	92.0
710	1.3631	58	.764	19.66	216	79.3
800	1.3518		.853	12.30	135.5	49.7
850	1.3493	61	.930	10.39	114.5	42.0
900	1.3465	62	.985	8.90	95.5	36.1
950	1.3450	62	1.042	8.50	89	34.3
1000	1.3456	61	1.105	8.00	82	32.7
1050	1.3454	61	1.160	8.0	81	32.4
1100	1.3435	61	1.21	7.5	77	30.3
1150	1.3430	60	1.27	7.15	73	28.8
1200	1.3413	61	1.323	5.50	61	22.4
1300	1.3394	60	1.435	4.70	48	19.0
1400	1.3377	64	1.545	3.30	36	13.2
1500	1.3344	65	1.655	1.34	13	4.8
1600	1.3328	65	1.770			
1700	1.3323	66	1.875			
1800	1.3322	64	1.980			

TABLE VI

RUN NUMBER 6
(Vertical Run - Upward)

Temperature = 25° C　　　　P = 380 mm. Hg.

Original Fluid (Distilled Water)　　　　Displacing Fluid (Sugar Solution)

n = 1.3324　　　　n = 1.3902

Viscosity = .8737 cp　　　　Viscosity = 3.7 cp

% Sugar = 36.01%

Cu. Cms. Produced	n = efflux	Rate cc/min.	Fract. Pore Volume	% Sugar in eff.	Wt. of sugar in eff. g/liter	% Original fluid in efflux
0		12				
155	1.3324	9½	.130			
200		8½	.221			
325		7	.358			
425	1.3324	5.7	.470			
500		5.1	.552			
600		4.6	.663			
700		4.2	.771			
825	1.3324	4	.902			
850	1.3324		.938			100
900	1.3330	3.7	.993	.30	4	99
910	1.3400		1.003	5.03	53	97.3
920	1.3468		1.014	9.71	102.5	75.3
930	1.3609		1.026	18.38	201	51.6
940	1.3811		1.042	30.50	344.5	17
955	1.3866		1.055	33.85	383	7.7
965	1.3890		1.064	34.05	401.5	3.5
985	1.3895		1.086	35.15	404	2.6
1000	1.3900	3.3	1.103	35.40	405	1.5
1025	1.3902					
1050	1.3902					
1100	1.3906	3.2	1.21	35.59	415	

TABLE VII

RUN NUMBER 7
(Vertical Run - Down)

Temperature = 26° C
P = 220 mm. Hg.

Original Fluid (Sugar Solution)
Displacing Fluid (Distilled Water)

n = 1.3902
n = 1.3324

Viscosity = 3.7 cp
Viscosity = .8737 cp

Sugar = 35.01%

cu. cms. Produced	n = efflux	Rate	Fract. Pore Volume	% Sugar in eff.	Wt. of sugar in eff.	% Original fluid in efflux
50	1.3902	3.6	.0551			
100	1.3902	4.2	.11			
200	1.3902	4.5	.221			
300	1.3902	4.6	.331			
400	1.3902	4.7	.442			
500	1.3902	4.5	.552	35.09	415	100
555	1.3846		.612	32.33	362	88.6
570	1.3796		.629	29.78	335.5	80.8
600	1.3767	5.7	.662	27.93	311.5	75.0
660	1.3704		.728	24.31	268.0	64.6
700	1.3654	6.4	.773	21.36	232	55.9
755	1.3590		.833	16.97	180	43.4
800	1.3600	6.7	.883	16.01	193	46.5
850	1.3602		.938	15.14	184	44.0
900	1.3590	7.0	.993	14.79	179	43.2
960	1.3560		1.0556	13.59	165	39.8
1000	1.3522	7.0	1.105	12.14	158	35.3
1055	1.3478		1.166	11.09	122.5	29.5
1100	1.3423	7.5	1.215	10.09	111.5	27.7
1150	1.3409		1.215	9.09	100.5	24.2
1200	1.3400	7.6	1.270	8.14	94.5	22.8
1300	1.3437	8	1.325	7.09	79	19.0
1400	1.3411		1.435	5.06	59	14.2
1500	1.3387	8.6	1.545	4.26	44	10.6
1600	1.3376		1.655	3.26	32.5	7.8
1700	1.3343	9.2	1.770	1.46	15	3.6
1800	1.3330		1.990	.4	4	.91
2000	1.3325	10.4	2.1	.4	4	.91
2000	1.3321	10.4	2.210			

TABLE VIII

RUN NUMBER 8
(Vertical Run - Upward)

Temperature = 27° C	P = 680 mm. Hg.
Original Fluid (Distilled water)	Displacing Fluid (Sugar Solution)
n = 1.3325	n = 1.3700
Viscosity = .8545 cp	Viscosity = 1.75 cp
	% Sugar = 24.75%

Cc. Cum. Produced	n = efflux	Rate cc/min.	Fract. Pore Vol.
0		12	
100	1.3325	10.0	.11
200		9.3	.221
300		8.0	.332
400		8	.442
500		7.1	.553
700		5.8	.773
800		5.2	.883
900	1.3340	4.2	.995
925	1.3405		1.02
950	1.3600	4.6	1.05
975	1.3690		
1000			
1025	1.3700	4.5	1.13
1050	1.3700		

TABLE IX

RUN NUMBER 2

Temperature = 27° C P = 620 mm. Hg.

Original Fluid (Sugar Solution)
n = 1.3709
Viscosity = 1.80 cp
% Sugar = 24.75

Displacing Fluid (Distilled Water)
n = 1.3323
Viscosity = .8545 cp

cu. cm. Produced	n = efflux	Rate cc/min.	Fract. Pore Volume	% Sugar in eff.	Wt. Sugar in eff.	% Original fluid in eff.
100	1.3709	4.5				
200	1.3709	4.5				
300	1.3709	4.6				
500	1.3708	4.8				
550	1.3709	4.9				
600	1.3708	5.0	.662			
610	1.3708	5.0	.673	24.05	272.5	100
625	1.3695	5.0	.690	23.13	262	96
650	1.3679	5.1	.717	22.08	250.4	92
700	1.3654	5.2	.773	21.43	233	85.5
750	1.3609	5.2	.827	18.65	201	73.8
800	1.3577	5.2	.883	16.73	178	65.4
850	1.3542		.938	14.91	158	58.0
900	1.3507	5.4	.993	12.26	128	47.0
950	1.3489+		1.048	11.16	116	42.6
1000	1.3466	5.6	1.103	8.81	90	33.0
1050	1.3437		1.160	7.73	79.5	29.2
1150	1.3385	5.7	1.269	4.43	44	16.1
1200	1.3378	5.7	1.325	3.73	37.4	13.7
1650	1.3328	5.8	1.820			
1700	1.3325		1.876			

TABLE X

RUN NUMBER 10

Temperature = 22° C   P = 220 mm. Hg.

Original Fluid (Distilled Water)
n = 1.3324
Viscosity = .9737 cp

Displacing Fluid (Sugar Solution)
n = 1.3385
Viscosity = 1.0 cp
% Sugar = 4.1%

cu. cms. Produced	n = efflux	Rate cc/min.	Fract. Pore Vol.
100	1.3324	13	.11
200	1.3324	13	.221
300	1.3324	12	.331
400	1.3324	11	.442
500	1.3324	10.5	.552
600	1.3324	10	.662
700	1.3324	9.8	.773
800	1.3324	9.5	.883
850	1.3324	8.3	.938
900	1.3370	8.0	.993
950	1.3372		1.049
1000	1.3378	7.9	1.105
1100	1.3382		1.21
1400	1.3385		1.546

TABLE XI

RUN NUMBER 11

Temperature = 25° C　　　　P = 200 mm. Hg.

Original Fluid (Sugar Solution)　　　　Displacing Fluid (Distilled Water)

n = 1.3385　　　　n = 1.3324

Viscosity = 1.0 cp　　　　Viscosity = .8937 cp

% Sugar = 4.15

Cc. Eff. Produced	n = efflux	Rate cc/min.	Fract. Pore Volume	% Sugar in eff.	Wt. of sugar in eff.	% Orig. Fluid in eff.
400	1.3385	10.5				
700	1.3385					
800	1.3385	10.7	.893	4.16	42	1.00
850	1.3385		.920	4.16	42	1.00
880	1.3363	10.7	.972	2.80	28	.67
900	1.3342		.995	1.26	13	.31
925	1.3340		1.02	1.06	11	.26
975	1.3335		1.075	.71	7	.17
1000	1.3330	10.7	1.105	.36	3.6	.086
1050	1.3326		1.160			
1150	1.3324	10.7	1.210			

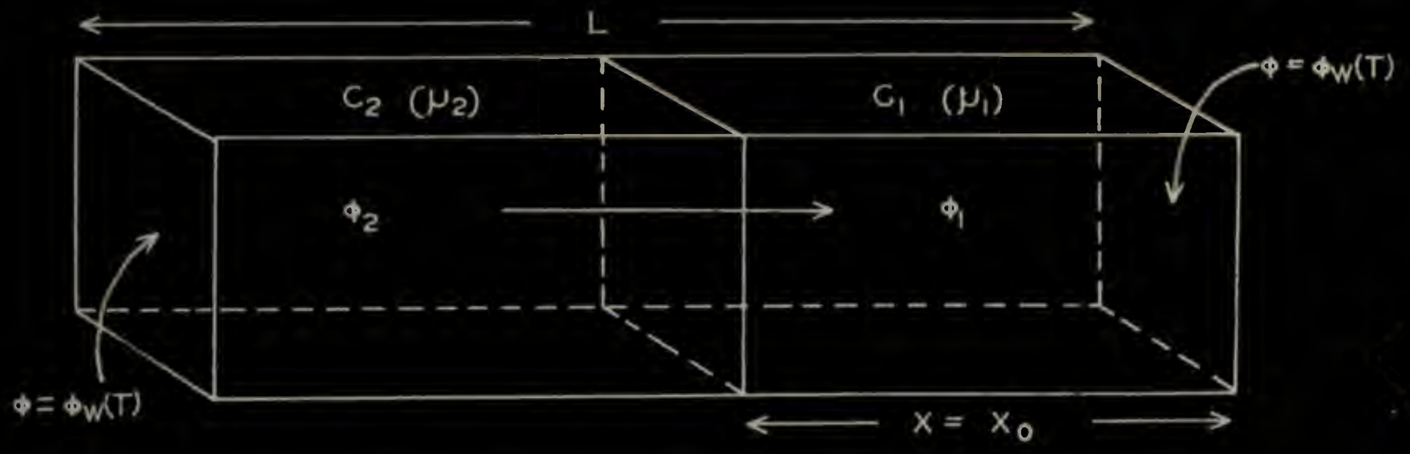
TABLE XII

COMPOSITE DATA

Viscosity Ratio Displacing Fluid / Original Fluid	Pore Volume Produced at Complete Recovery	Per cent of Orig. Fluid Recovered at One Pore Volume	Index of Refraction of Total Displaced Liquid
.110	4.1	72.7	1.5000
.230	2.6	85.8	1.5220
.405	1.37	89.7	
.875	1.26	95.7	1.5501
4.25	1.2	99.0	

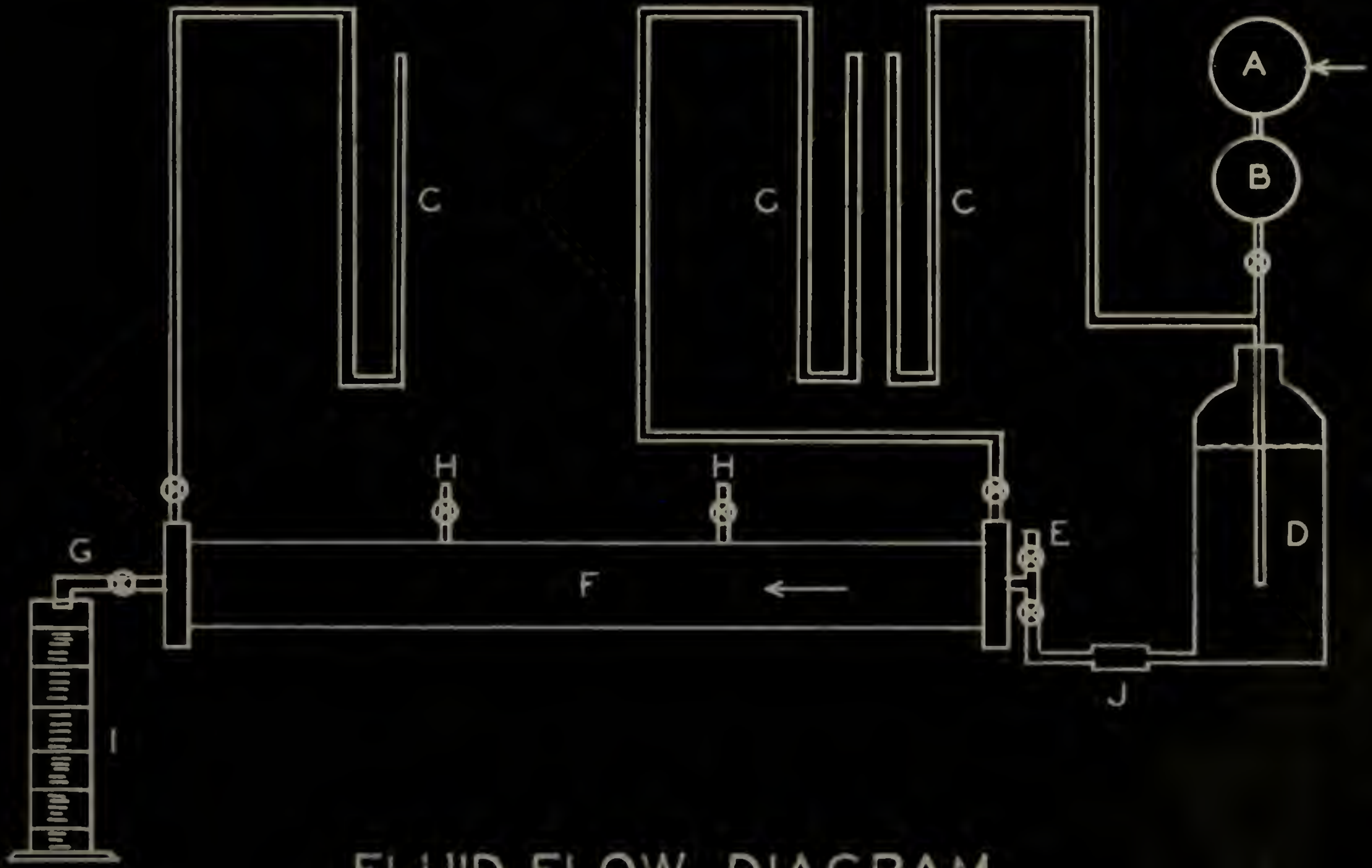
FIGURE

FIGURE I



A LINEAR ENCROACHMENT SYSTEM
AFTER MUSKAT

FIGURE II



FLUID FLOW DIAGRAM

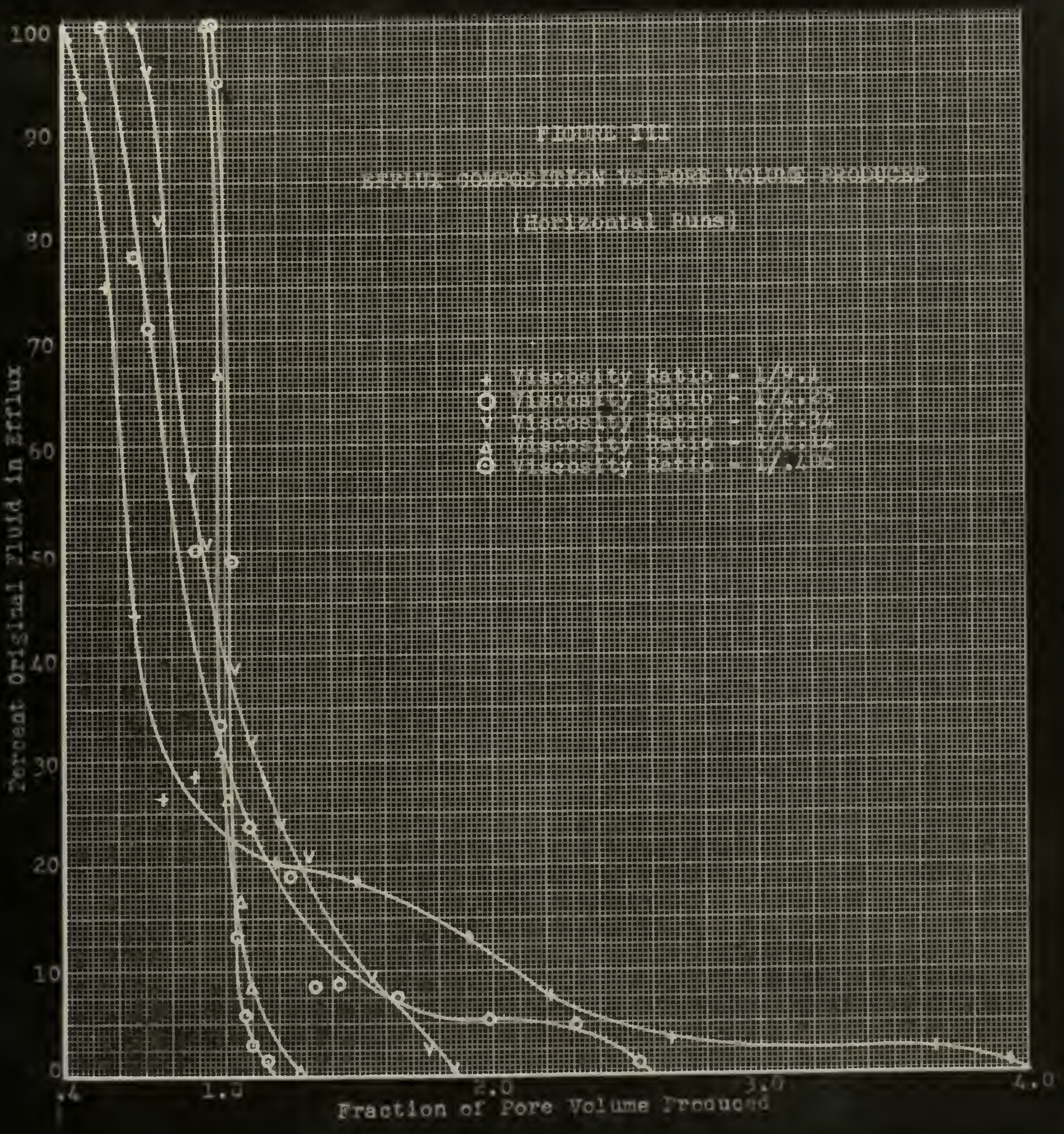


FIGURE III
EFFLUX COMPOSITION VS PORE VOLUME PRODUCED
(Horizontal Runs)
+ Viscosity Ratio = 1/9.1
○ Viscosity Ratio = 1/[illegible]
v Viscosity Ratio = 1/[illegible]
Δ Viscosity Ratio = 1/[illegible]
⊙ Viscosity Ratio = 1/[illegible]
Percent Original Fluid in Efflux
100
90
80
70
60
50
40
30
20
10
0
.4
1.0
2.0
3.0
4.0
Fraction of Pore Volume Produced

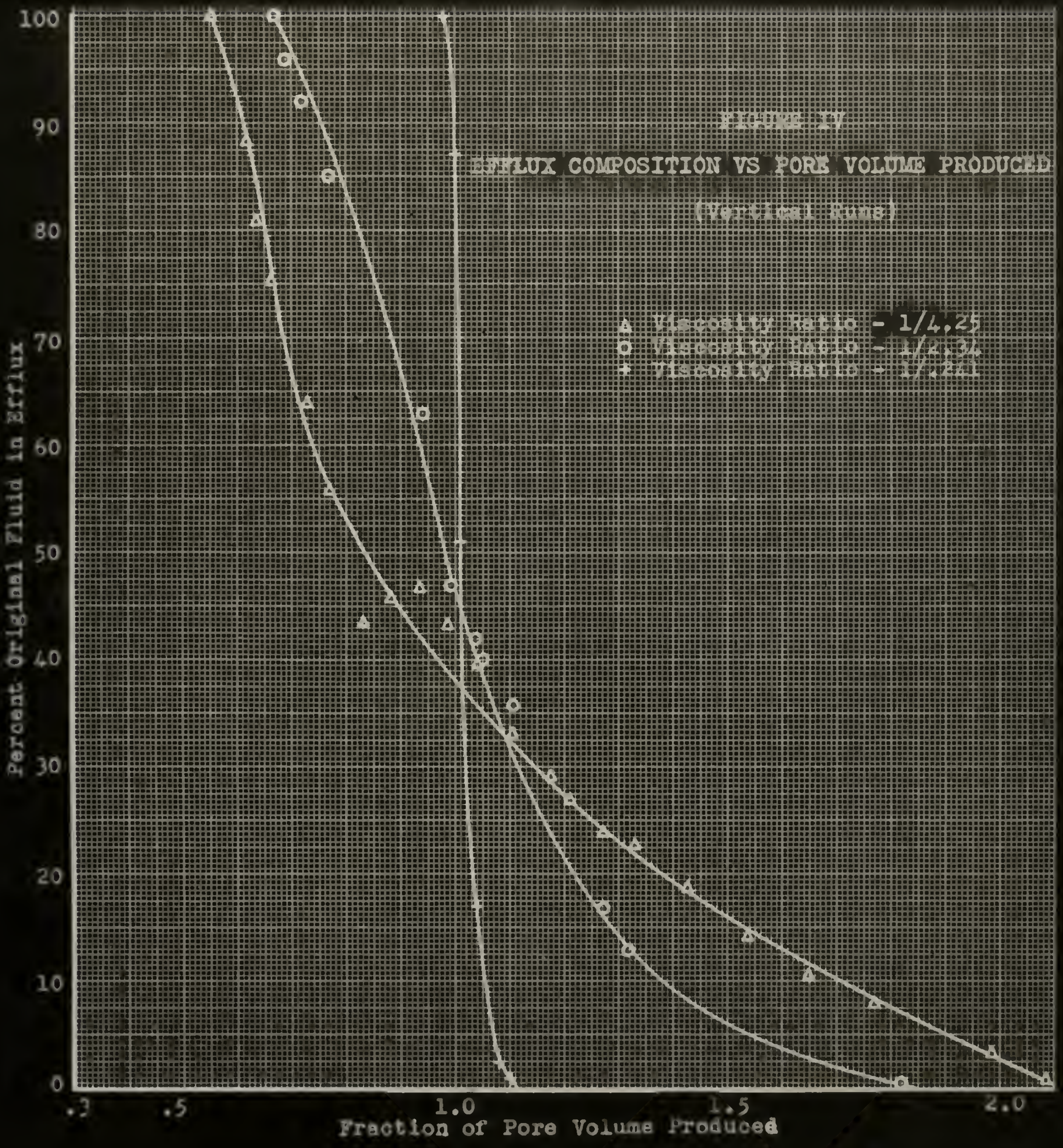


FIGURE IV

EFFLUX COMPOSITION VS PORE VOLUME PRODUCED

(Vertical Runs)

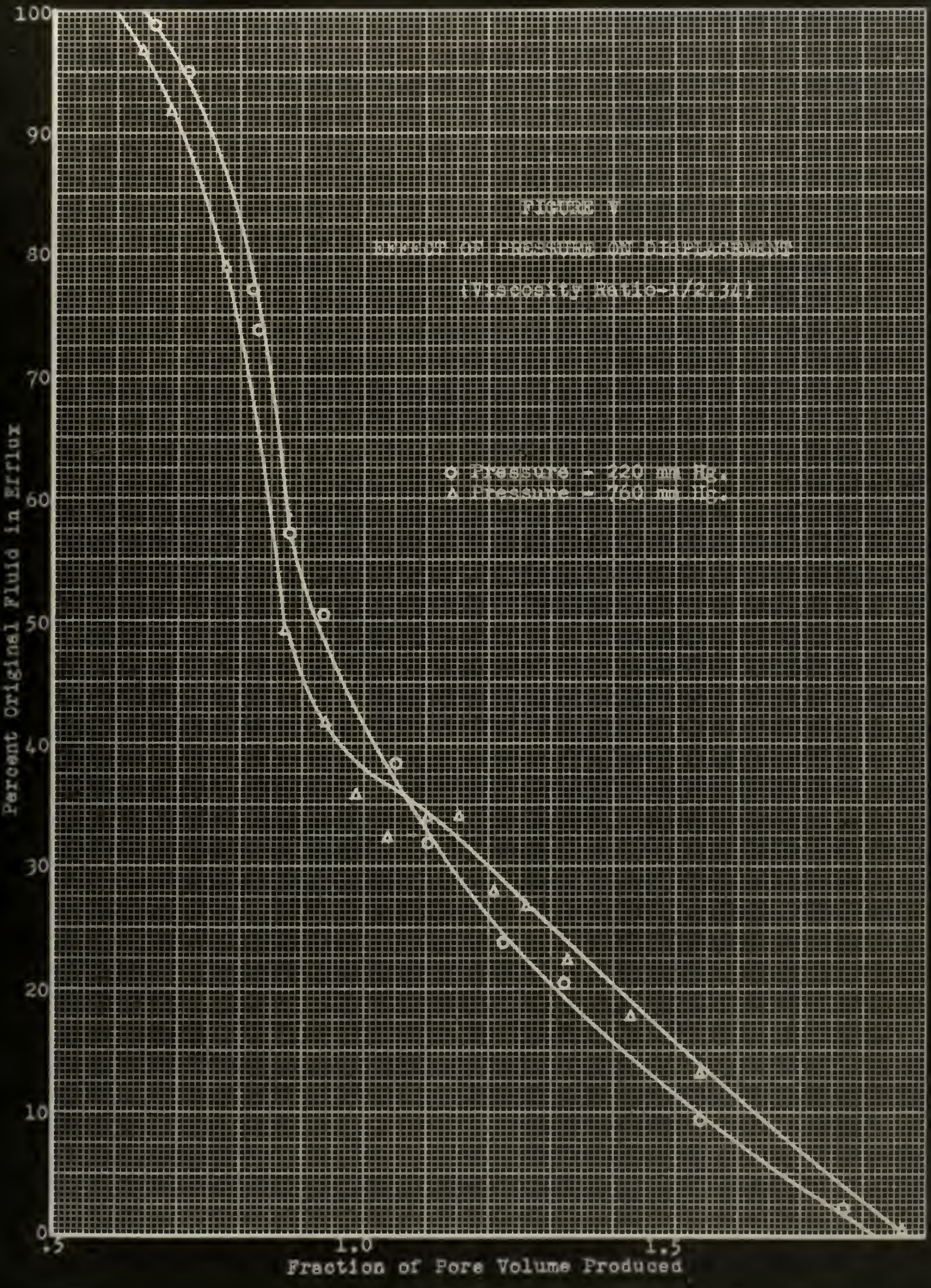


FIGURE V

EFFECT OF PRESSURE ON DISPLACEMENT

(Viscosity Ratio=1/2.34)

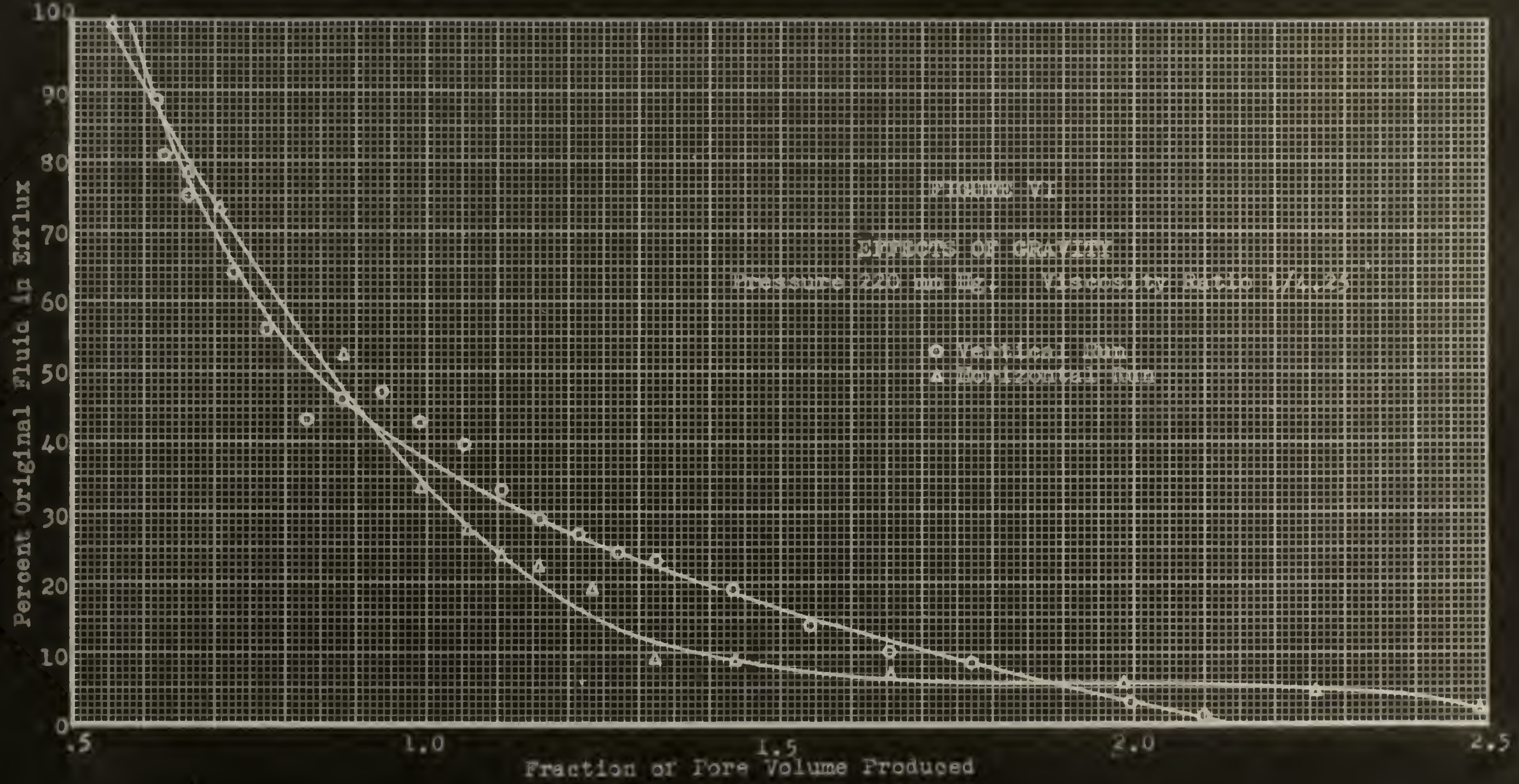


FIGURE VI

EFFECTS OF GRAVITY

Pressure 220 mm Hg. Viscosity Ratio 1/4.25

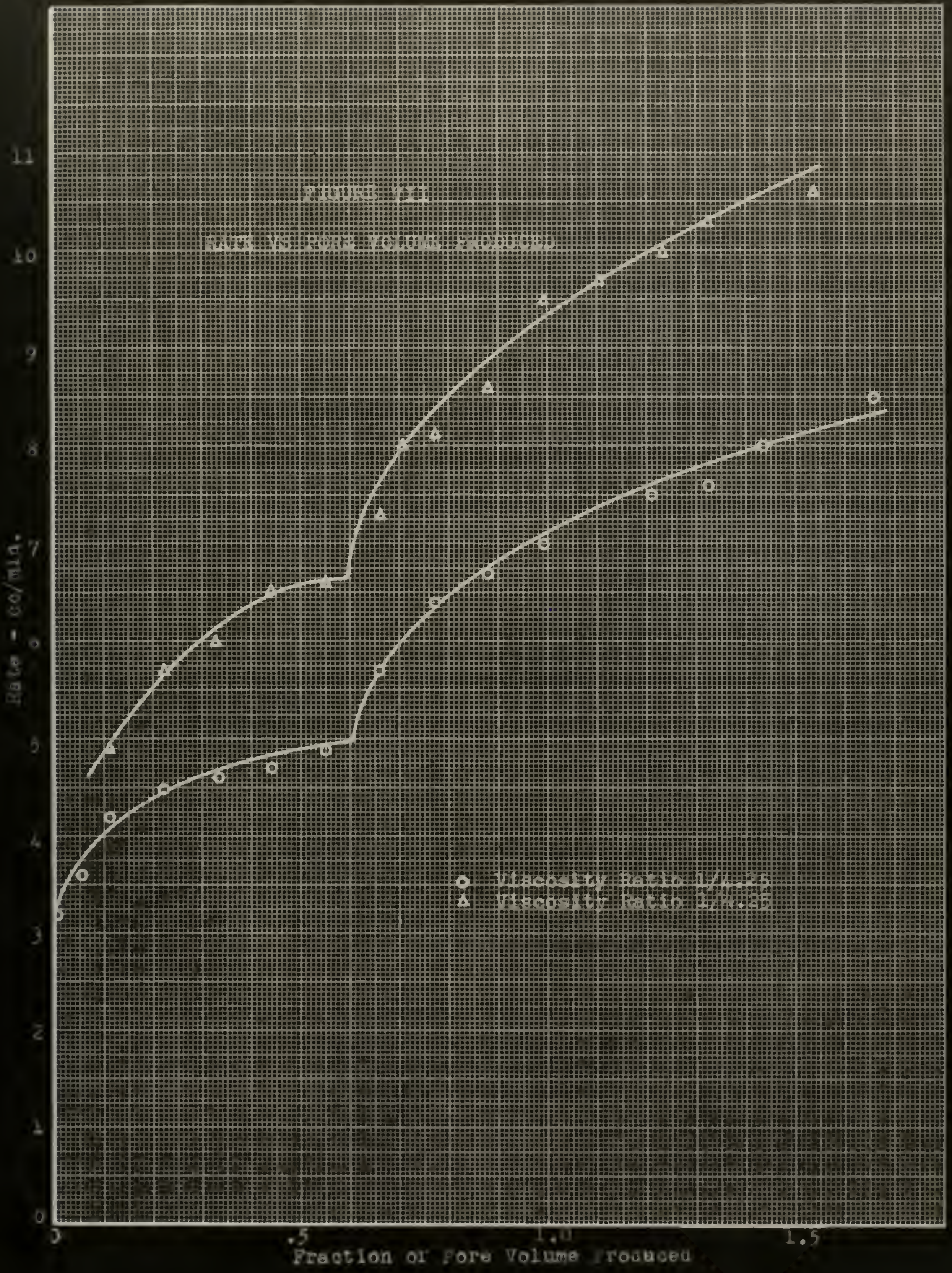


FIGURE XII

RATE VS PORE VOLUME PRODUCED

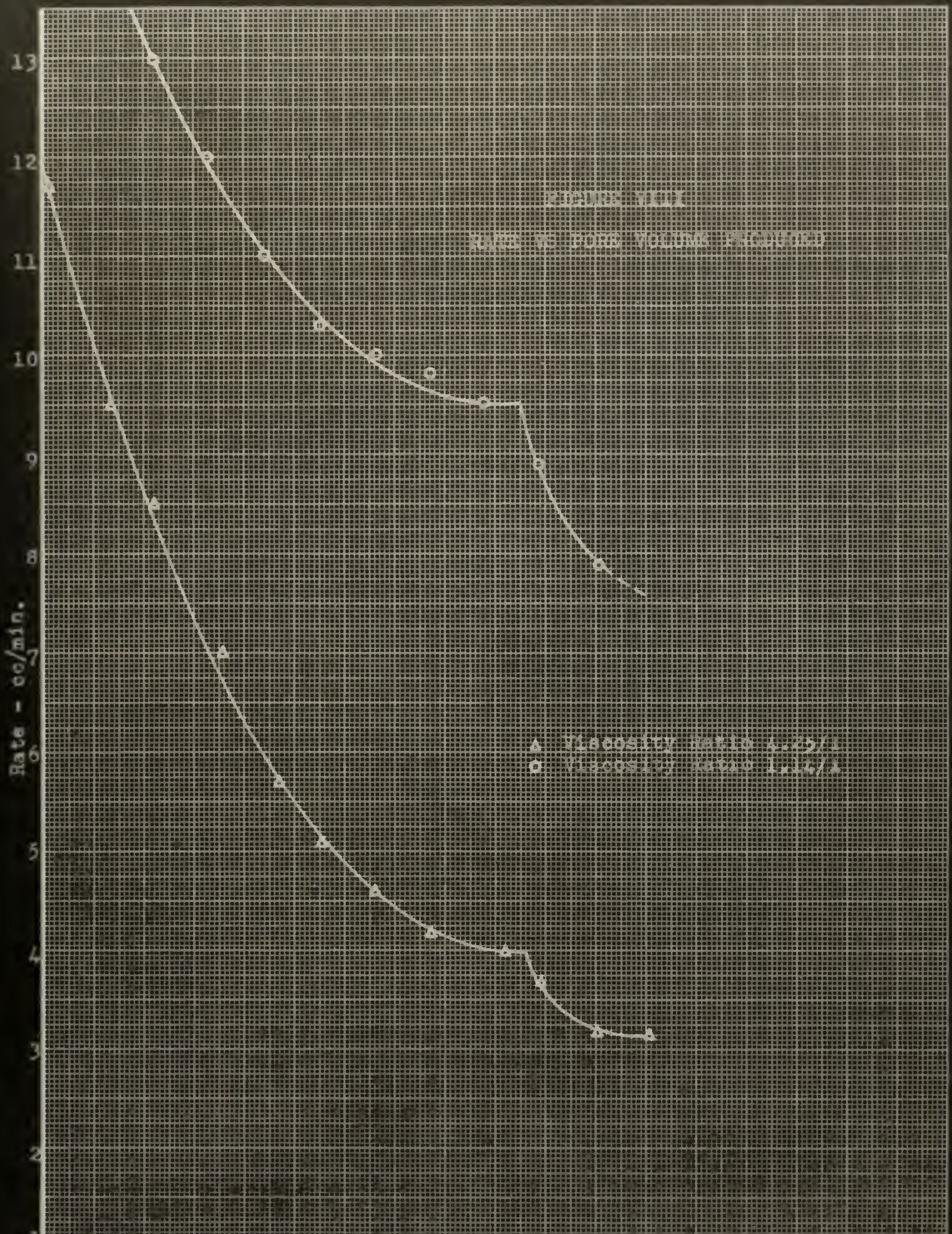


FIGURE VIII

RATE VS PORE VOLUME PRODUCED

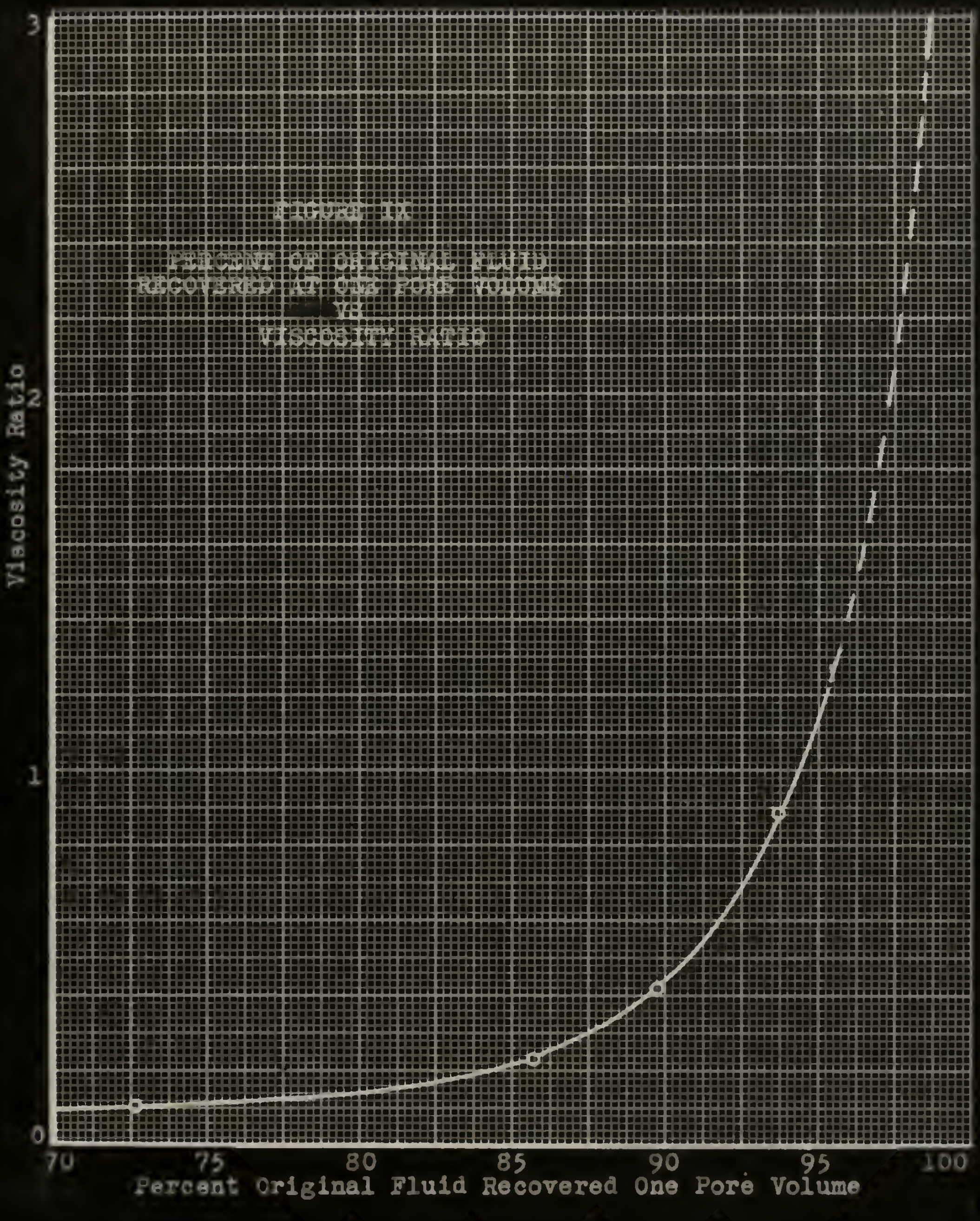


FIGURE IX

PERCENT OF ORIGINAL FLUID
RECOVERED AT ONE PORE VOLUME
VS
VISCOSITY RATIO

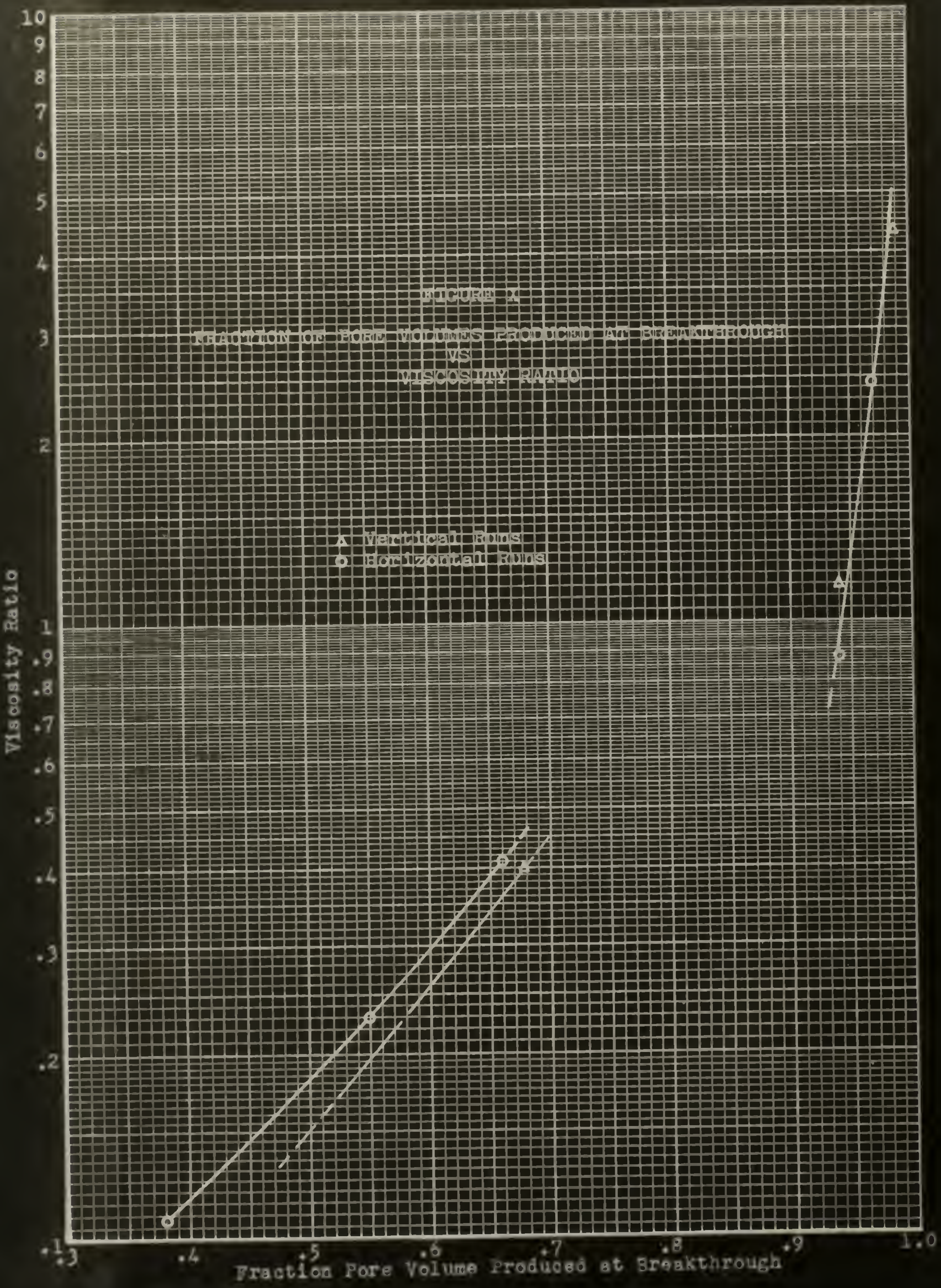


FIGURE X

FRACTION OF PORE VOLUMES PRODUCED AT BREAKTHROUGH
VS
VISCOSITY RATIO

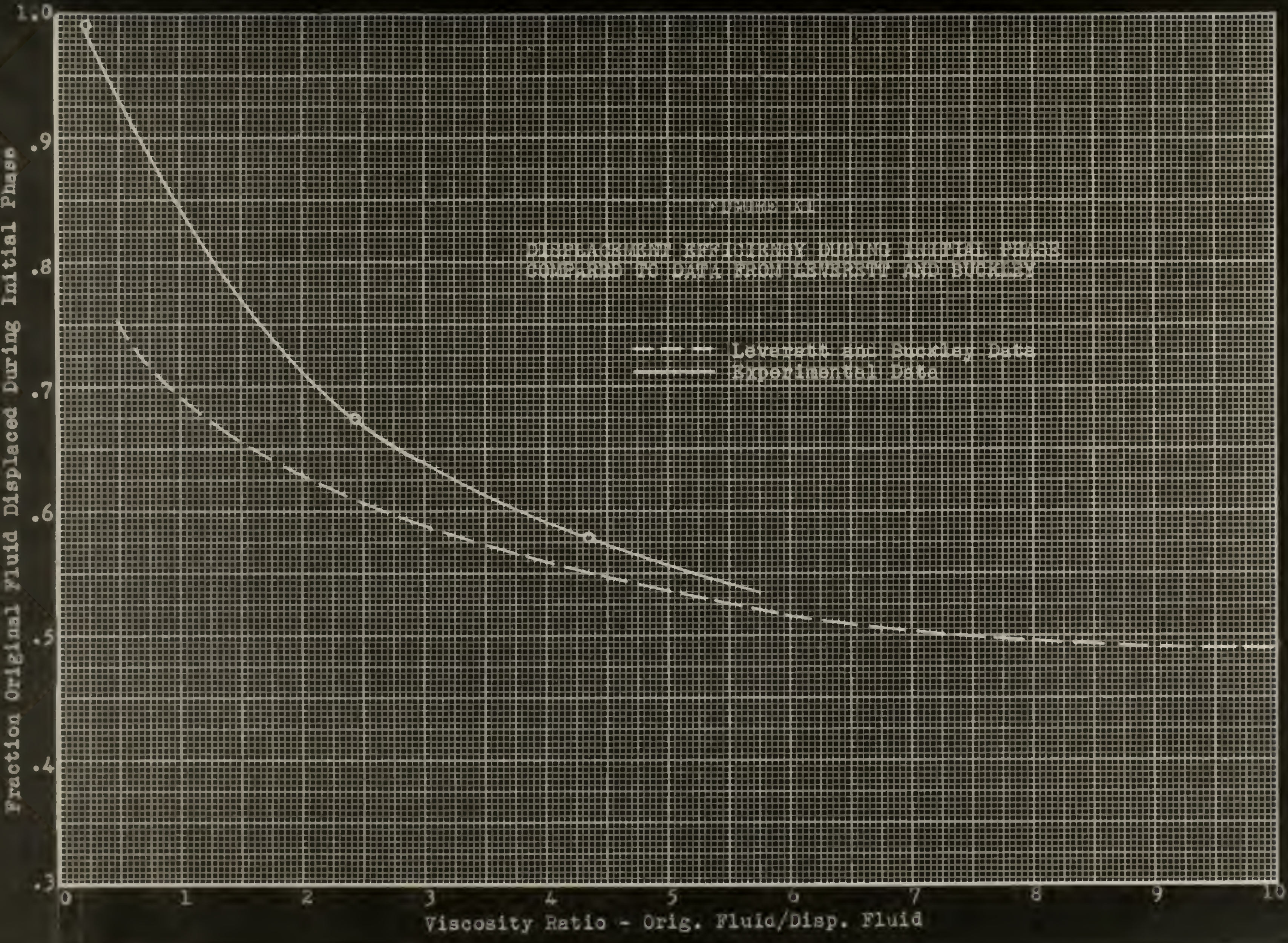


FIGURE XI

DISPLACEMENT EFFICIENCY DURING INITIAL PHASE COMPARED TO DATA FROM LEVERETT AND BUCKLEY

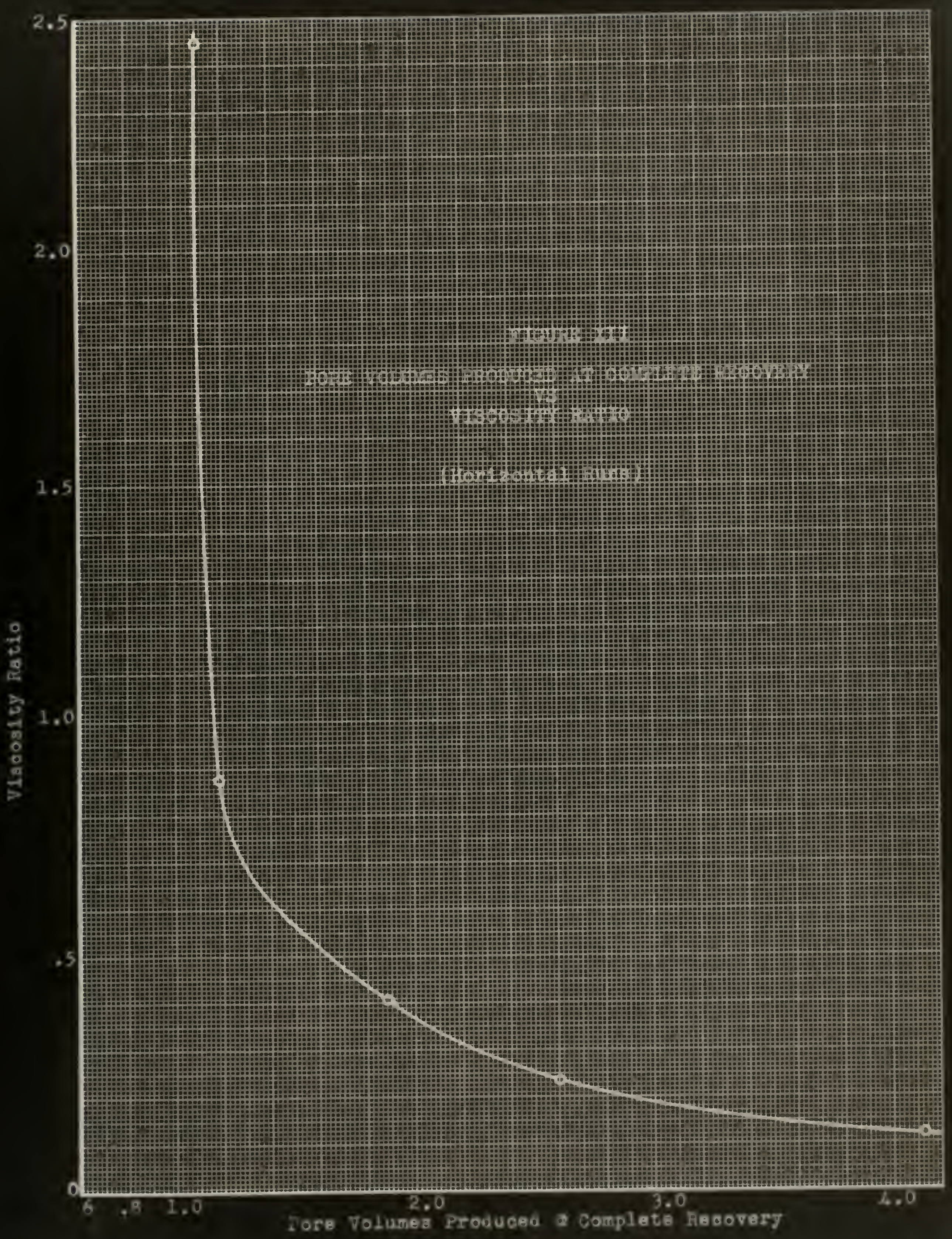


FIGURE XII

PORE VOLUMES PRODUCED AT COMPLETE RECOVERY
VS
VISCOSITY RATIO

(Horizontal Runs)

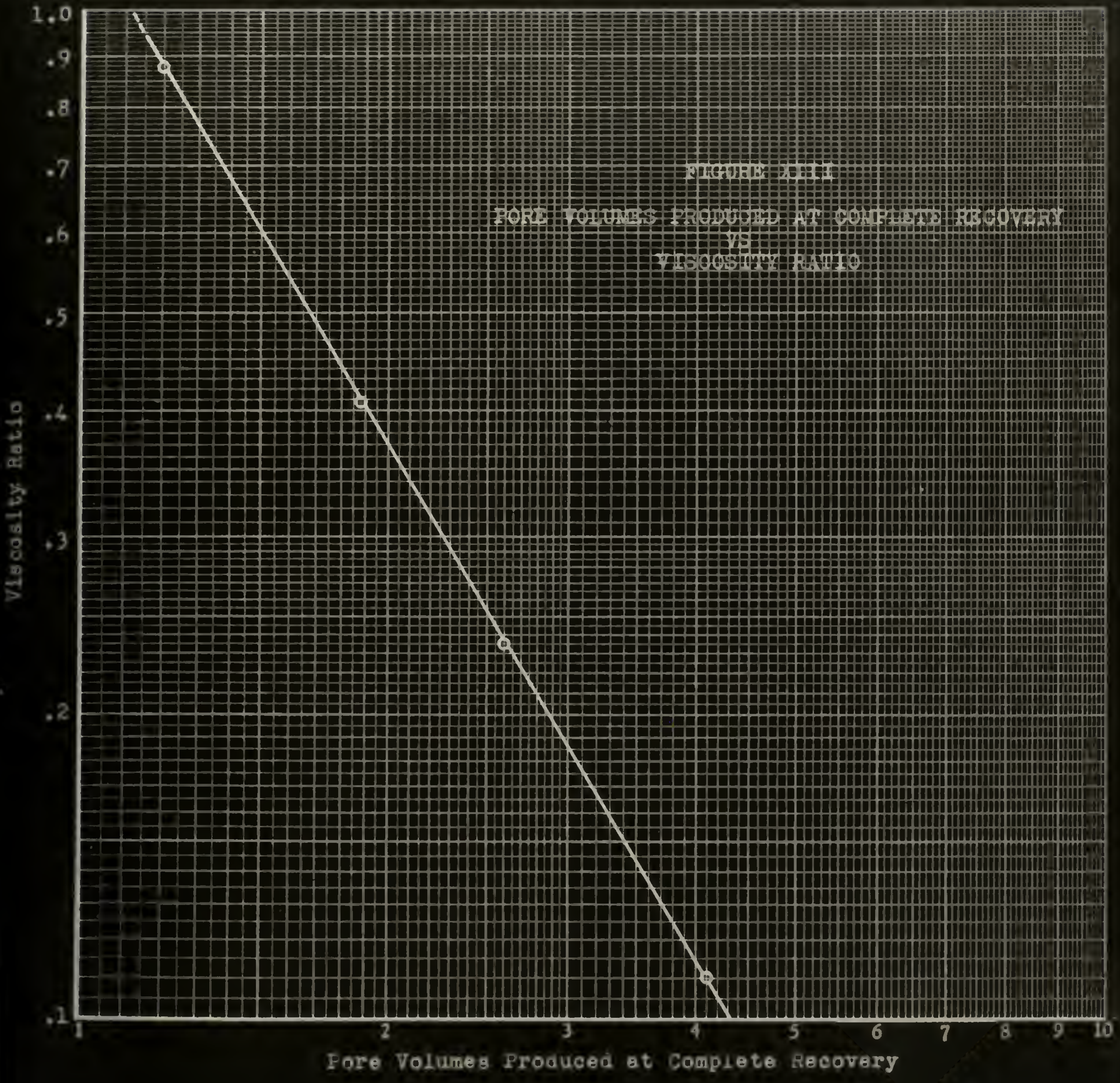


FIGURE XIII

PORE VOLUMES PRODUCED AT COMPLETE RECOVERY
VS
VISCOSITY RATIO

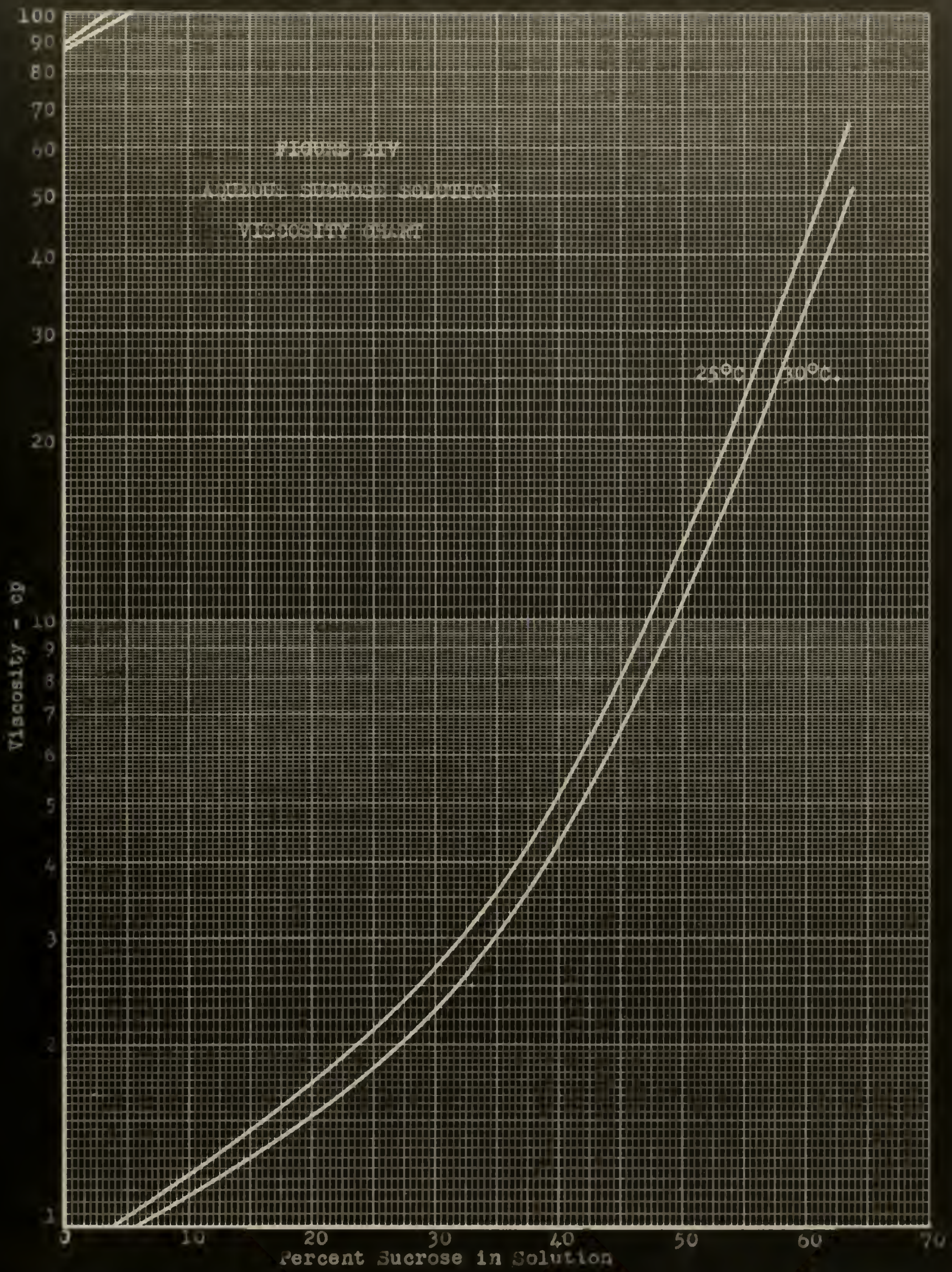


FIGURE XIV

AQUEOUS SUCROSE SOLUTION

VISCOSITY CHART

CHAPTER VII

ANALYSIS OF DATA

Theoretical Approach

An equation expressing the behavior of two miscible fluids of different viscosities, in the case of linear displacement, has been derived by Muskat (13). In developing this equation he simplified the system to one in which the two fluids are moving in a channel of areal extent that is small compared to the length. This would be approximated physically by a narrow channel of high permeability. Figure 1 illustrates such a linear system.

For a system as shown in Figure 1 Muskat arrives at the following equation:

$$\left(\frac{\mu_o}{\mu} - 1\right)\left[\frac{\mu_o}{\mu}(1 - \epsilon) + \epsilon + 1\right]\frac{2\Delta\phi c_1 t}{L^2} = 0;$$

Equation (1)

Where: k = permeability

p = pressure

Φ = potential function = kp if gravity is neglected

μ = viscosity

c = fluidity = $1/\mu$

L = length

t = time

$\Delta\Phi$ = difference in potential function existing at the two boundaries.

$\epsilon = \frac{C_1}{C_2} = \frac{\mu_2}{\mu_1}$

X = L minus distance flood front has traveled.

Since t is included in the combined term $\frac{2\Delta\Phi C_1 t}{L^2} = 0$, it shows that at any particular state of the displacement the time necessary to reach this state varies directly with the viscosity of the displaced fluid, directly as the total length of the system and inversely as the average potential gradient $\frac{\Delta\Phi}{L}$. From this it is seen that as the interface advances its rate of advance is accelerated if the displacing fluid has the higher fluidity ($\epsilon<1$) whereas it is retarded if the displacing fluid has the lower fluidity ($\epsilon > 1$).

The total time for the interface to travel the total length is given by setting X_0 equal to zero in equation one and solving for $t_{max.}$[1]

$$t_{max.} = \mu_1 (1 + \mu_2/\mu_1) \frac{fL^2}{2\Delta\Phi} \qquad \text{Equation (2)}$$

where f is the porosity of the medium.

From this relation it is evident when $\mu_2 < \mu_1$ the displacement time is less than that for a single fluid.

$$t_{max.}^{\circ} = \frac{\mu_1 f L^2}{\Delta\Phi} \qquad \text{Equation (3)}$$

It may also be noted that when μ_2 is very much smaller than

μ_1 a maximum decrease in $t_{max.}$ is attained, thus in this limiting case the drive by a displacing fluid of very low viscosity would cut by half the time required for the column of original fluid to pass through the system. When $\mu_2 > \mu_1$ it can be seen that $t_{max.}$ will always exceed $t_{max.}^{\circ}$, and will ultimately become infinite as μ_2 becomes infinitely large.

Sample Calculations

In all of the experiments the only physical properties of the solutions measured were temperature and index of refraction. From these two measurements could be calculated the amount of sucrose in the solution and thus the fraction of the original fluid in the effluent stream.

As an example one calculation is shown for converting the index of refraction to fraction of original fluid in the efflux. Data is taken from Run No. 2, Table III, when 900 cc of fluid had been displaced.

Taking the index of refraction 1.4080 at 25° C, for the original fluid in the core, and referring to the table, "Index of Refraction of Aqueous Solutions of Sucrose," in the Handbook of Chemistry and Physics, the per cent of sucrose was determined for a temperature of 20° C. to be 44.6. A temperature correction of + .43 was applied giving a per cent by weight of 45.03. From the table, "Specific Gravity of Aqueous Sucrose Solutions," in the same reference it was determined that this per cent of sucrose equals 541.3 grams per liter.

When 300 cc of fluid had been displaced from the core the index of refraction of the efflux was measured and found to be 1.3520 at a temperature of 25° C. From the Handbook of Chemistry and Physics the corrected per cent of sucrose was determined to be 12.32 and the weight of sucrose in grams per liter 130. To get the fraction of the original fluid present in the effluent stream the following relation is used:

$$\text{Fract. of Orig. Fluid in Eff.} = \frac{\text{g./ltr. sucrose in efflux}}{\text{g./ltr. sucrose in orig. fluid}}$$

Substituting the above values gives:

$$\text{Fract. of Orig. Fluid in Eff.} = \frac{130.0}{541.6} = .240$$

Discussion of Experimental Results

The results obtained in this series of experiments are tabulated in Tables I through XII. These tables have been simplified by including only the pertinent data. In addition the original data contained index of refraction of the total solution displaced and total elapsed time, which were not used in this work. In Runs 1 through 5 the rate of flow was not recorded and in Run 9 the screen at the inlet end of the core became plugged and thus the rates recorded during this run were of no benefit.

All runs were made with the core in a horizontal position except runs number 6, 7, 8, 9. The core was placed in a vertical position for these runs. When a heavy fluid was displaced by a lighter fluid, the lighter fluid was introduced at the upper end of the core; if a light fluid was being displaced

by a heavier fluid it was introduced at the lower end of the core. Thus it was felt that the results of these drives were free from all effects of gravity.

Figures III and IV illustrate graphically the results of eight runs carried out at various viscosity ratios. Viscosity ratio as used in this paper will be the viscosity of the displacing fluid divided by the viscosity of the original fluid unless otherwise noted.

Figure III presents the results of the horizontal runs for various viscosity ratios. When the viscosity ratio is small as shown by the plot for a viscosity ratio of 1/3.2 the displacing fluid breaks through before half a pore volume has been produced. Following this break through there is a fairly constant decrease in the amount of original fluid in the efflux until approximately .8 of a pore volume is produced. From this point to a production of 1.6 pore volumes there appears to be unstable producing conditions as evidenced by the scattered points on the plot. The curve then tends to level off with very slight decrease in the amount of original fluid in the efflux. This appears to form a plateau on the plot. It is possible that this could be caused by gravity segregation since there was definite evidence of this when the progress of the flood front was followed visually as it moved along the core. The heavier fluid appeared to channel along the bottom of the core. When the core was rotated to check the possibility that the permeability was greater along

one side of the tube, the channeling effect was still along the bottom indicating that it could be caused by gravity.

Referring again to Figure III when the viscosity ratio approached unity or larger, as illustrated by the plot for a ratio of 1/1.14, the displacing fluid does not break through until over .8 of a pore volume is produced. The amount of original fluid in the efflux drops off rapidly with no apparent plateau in the curve. This should follow if the plateau is due to gravity segregation.

Similar runs were made with the core in a vertical position and the results plotted in Figure IV. From this it can be seen that the fraction of original fluid produced at break through is essentially the same as in the horizontal runs and thus is not appreciably affected by gravity. There was no indication of a plateau with a viscosity ratio as low as 1/4.22 which bears out the supposition that this leveling off, in the cases illustrated in Figure III, was caused by gravity segregation.

From Figures III and IV it would appear that the mechanics of displacement involving two miscible fluids is similar to that of two immiscible liquids as described by Buckley and Leverett (10). The displacement can be divided into two phases. The initial phase occurs before the break through of the displacing fluid and is a piston like displacement. In the subordinate phase, which follows the break through, the original fluid is produced by a dragging action.

[illegible]

[illegible]

Similar [illegible]

From Figures III and IV it would appear that the [illegible] this phase differs in the case of miscible fluids only in that 100 per cent of the original fluid can be produced which is not possible with immiscible fluids.

As a check on the accuracy of the plots and on the completeness of recovery of the original fluid from the core the area under each curve was measured. With 100 per cent recovery of the original fluid the area under each curve should be 100 units. In all cases the error was never more than 2 per cent.

The cause of the period of unstable production is not known, though it would seem possible that it could be due to streaks of variable permeability which would allow by-passing of small areas. At a later time the original fluid from these areas would reach the outlet end of the core and temporarily increase the amount of original fluid in the efflux.

To see what effect pressure would have on the displacement picture two runs were made using a viscosity ratio of 1/2.44. The pressure differential for one run was 250 mm. mercury and for the other run was 760 mm. mercury. The results plotted in Figure V show that an increase in pressure tends to cause a break through to occur earlier and to require more pore volumes before complete displacement of the original fluid takes place.

To study the possible effects of gravity segregation, runs were made with the core both in the horizontal and

vertical position. Two runs with a viscosity ratio of 1/2.25 were plotted in Figure VI. From this plot it can be seen that in the horizontal run where it is possible for gravity segregation to take place the curve is not as simple or smooth as the curve for the vertical run. However, the vertical run does break through earlier than the horizontal run, but the piston, shows up in the horizontal run thus requiring more pore volumes through-put before complete displacement takes place.

Though it is not included herein, a similar plot for a viscosity ratio of 1/2.44 shows similar deviations between the two curves.

According to Muskat (15) the effect of viscosity ratio on the rate of flow of the efflux can be calculated by Equation (1). If the original fluid is being displaced by one of lower viscosity the overall resistance of the system will be lowered and the rate of efflux increased. If the original fluid is displaced by one of higher viscosity the overall resistance is increased and the rate of efflux decreased.

From Figure VII it is noted that there is an appreciable increase in efflux rate as soon as injection of the lower viscosity fluid commences. This increase in efflux rate tends to gradually drop off until the point is reached where the displacing fluid breaks through. Then there is a sharp increase in efflux rate with an immediate tapering off

of the rate till the point is reached where the original fluid is completely displaced and the efflux rate is constant.

This behavior is similar to the qualitative description given concerning the nature of the effects of the viscosity difference between encroaching and displaced liquids in the case of direct drive by Muskat (15). This should follow since the injection of the displacing fluid into a small opening in one end of a long cylindrical core and producing from a small opening in the other end would in many ways approximate the physical conditions of a direct drive between two wells.

The same pattern is shown by Figure VIII except in this case the original fluid is being displaced by one of higher viscosity, thus there is a decrease in efflux rates in place of an increase. The curve for a viscosity ratio of 1.34/1 was affected by a plugging of the screen at the inlet end of the core during the run. However, it was included since it illustrates the qualitative description given by Muskat.

To indicate a measure of the efficiency of the various drives as a function of the viscosity ratio, Figures IX, X, and XI were constructed. Figure IX illustrates the efficiency of recovery when one pore volume of fluid has been displaced from the core. From this it can be seen that as the viscosity ratios become smaller than .2 the per cent of original fluids displaced, when one pore volume has been produced, falls off

rapidly. With the viscosity ratio unity or larger there is very little increase in the per cent of original fluid displaced. Thus it can be seen that as long as the viscosity ratio is .5 or greater 90 per cent or more of the original fluid will be displaced when one pore volume has been produced.

As another measure of the efficiency of displacement, the pore volume produced when the displacing fluid breaks through was plotted against the logarithm of the viscosity ratio in figure 20. This plot appears to give a straight line up to a viscosity ratio of .4 with a break from this point to a viscosity ratio of approximately .8. At this point there was a return to linearity but at a new slope. Unfortunately runs were not made with viscosity ratios in the region of departure from linearity so that information on this region is missing. It would seem, as indicated by Figure 20, when the viscosity ratio is .5 or greater that the recovery efficiency would be very high.

Figure 21 shows a plot of pore volumes of original fluid produced during the initial phase versus viscosity ratio, where the viscosity ratio is equal to the viscosity of the original fluid divided by the viscosity of the displacing fluid. For comparison data given by Buckley and Leverett (10), concerning the effect of oil viscosity on the efficiency of the initial phase of a water flood in a typical sand, is also plotted in the same figure.

The shape of the two curves in the above plot is

similar; however, the effect of viscosity ratio is greater in the case of miscible fluids. This might be explained by the fact that in the case of immiscible fluids all of the original fluid is not active and is not moved at any time during the displacement; thus limiting the range of the fraction of original fluid that could be displaced during the initial phase.

Figures XII and XIII give the number of pore volumes required before complete recovery of the original fluid is obtained. Figure XII indicates that the number of pore volumes required for complete recovery, for a viscosity ratio of .2 or greater, would be slightly larger than one. The number of pore volumes required as the viscosity ratio gets smaller does not decrease rapidly until a viscosity ratio of .4 is reached. From here the increase is very great even with only slight reductions in viscosity ratio.

The same data plotted on log paper gives a straight line with viscosity ratios of .3 or lower.

Referring to the article, "Some Experiments on the Mobility of Interstitial Waters" (13), where data is contained on the displacement from a sandstone core of radio active water by non active water the following conclusions are given: the displacing fluid breaks through when between .6 and .9 of a pore volume has been produced, 50 to 80 per cent of the original fluid was recovered when one pore volume had been produced, and over 1.5 pore volumes were produced before complete recovery of the original fluid occurs.

The data obtained during the present series of experiments, for a viscosity ratio comparable to that used in arriving at the results described above, does not check the above conclusions. This data indicates that over 80 per cent of the original fluid is produced before the displacing fluid breaks through, approximately 95 per cent of the original fluid is displaced when one pore volume has been produced, and less than 1.2 pore volumes are required for complete recovery of the original fluid.

Thus even greater mobility of the interstitial water is indicated than was shown in the previous experiment. This could be due to the higher permeability that undoubtedly existed in this experiment but it would not seem that this alone would account for this difference.

It would appear that the shape of the displacement curves, Figures III and IV could be useful in studying the mechanism of displacement. Equation 2 indicates that the shape of the displacement curves might be an indication of the degree of permeability variation present in the porous media. However, work done by Fowler and Brown (10) displacing one fluid by another in a pipe line indicates that the shape of the displacement curves is a result of the parabolic interface formed in each of the capillary openings.

It would seem possible that the shape of the displacement curves could be affected by both of the above factors.

Errors Involved

The use of a refractometer to measure index of

refraction which in turn is converted to per cent of sucrose in an aqueous solution limits the accuracy of the results to the accuracy of the instrument used. In this work a Spencer Abbe-type Refractometer was used. The scales on it could be read directly to the third decimal place and the fourth estimated with an accuracy of 0.0002. This gave an accuracy of 0.2 per cent in measuring the per cent of sucrose in solution.

The accuracy of the refractometer was checked before any runs were made by use of the glass test slab included with the instrument for which the index of refraction was known.

Index of refraction and viscosity of the solutions are both affected by changes in temperature. Since the temperature seldom changed more than a degree during a series of measurements it was felt that any temperature effects were within the experimental error. No appreciable effects on the data were observed that could be attributed to changes in temperature.

A small error was certainly introduced in the measurement of pressure differentials with a liquid manometer and volumes displaced with a graduated cylinder since there is some human error in reading fluid levels. These readings are considered to be well within the range of experimental error and sufficiently accurate for the computations necessary in this work. The degree of accuracy of these readings is indicated by graphical integration of the areas under the curves drawn in Figures III and IV. The majority of these areas were in error by less than one per cent and all were less than two per cent.

CHAPTER VIII

SUMMARY

A study was made of the displacement of one miscible fluid by another from a partially consolidated synthetic sandstone core. This core was composed of 80 to 140 mesh Oil Creek silica sand and colloidal silica. The porosity of the core was 20.7 per cent and the air permeability was 3.02 darcies. This core 5.55 centimeters in diameter and 15.7 centimeters in length was assembled with pressure taps in each end plate to permit determination of pressure drop across the core. The core was saturated with a fluid of known viscosity, then this fluid was displaced by another miscible fluid of different viscosity. The rate of efflux, total amount of fluid produced, and data to calculate the per cent of original fluid in the efflux was measured and recorded at regular intervals.

The solutions used in these experiments were made by dissolving various amounts of cane sugar (sucrose) in distilled water. The amount of sucrose in solution determined the viscosity of the fluid. Four solutions were used plus distilled water to get a range of viscosity ratios. The four

solutions contained 4.1, 14.6, 35.1, and 45.08 per cent of sucrose by weight.

Since information of a fundamental nature was sought it was decided to vary only the viscosity ratio of the displacing fluid to the original fluid and to maintain all other factors as nearly constant as possible. The range of viscosity ratios examined in these experiments ran from .11 to 9.1.

The data gathered in this work was used to arrive at several conclusions regarding the affect of viscosity ratio on the mechanics and the efficiency of displacement of one miscible fluid by another.

CHAPTER IX

CONCLUSIONS

1. The mechanics of the displacement of one miscible fluid by another is similar to the mechanics of displacement where the two fluids are immiscible. The displacement can be divided into two phases, the initial phase where there is a piston like displacement and the subordinate phase where the fluid is displaced by a dragging action.

2. When the viscosity ratio is smaller than unity the rate will increase, if the viscosity ratio is larger than unity the rate will decrease.

3. Increasing pressure differential and maintaining the same viscosity ratio causes the break through of the displacing fluid to occur earlier and requires more pore volumes to obtain complete displacement of the original fluid.

4. If gravity segregation is present more pore volumes will be required to obtain complete recovery.

5. Efficient displacement in the initial phase is obtained with viscosity ratios of .8 or greater. More than 90 per cent of the original fluid is recovered when one pore volume has been produced.

6. For the most efficient complete recovery of original fluid the viscosity ratio should be .8 or greater.

7. Viscosity ratios of .3 and lower do not produce efficiently in the initial phase and require 3 or more pore volumes for complete recovery.

8. There is very little increase in the efficiency of displacement when the viscosity ratio is increased beyond unity.

9. Further study to determine if a relation exists between the shape of the displacement curves and permeability variation is indicated in view of the importance of this factor in the production of petroleum.

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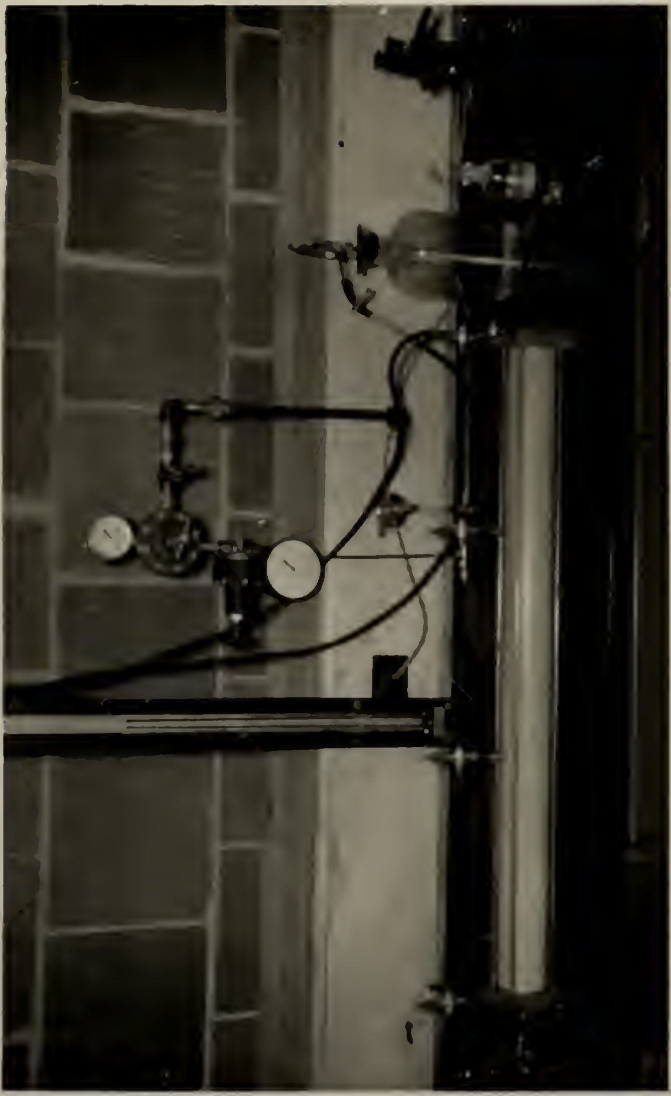
APPENDIX



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